We were asked to present this LOI:

Barium Tagging in Xenon Gas for Neutrinoless Double Beta Decay

The NEXT Collaboration *

October 1, 2020

Snowmass LOI submitted to the attention of Working Groups:

NF05: Neutrino properties; IF9: Cross cutting instrumentation; RF04: LNV processes

1 Barium Tagging

It is well understood that the only known practically sensitive way to establish the Majorana nature of the neutrino is via direct and robust observation of neutrinoless double beta decay ($0\nu\beta\beta$). This question is central to understanding the physics of neutrino mass, likely the only observed manifestation of physics at energy scales above the electroweak, and compelling as a potential window into the mystery of the dominance of matter over antimatter in the Universe.

...etc

- The best-case scenario, the neutrino is Majorana and either mass ordering is inverted or LNV TeV scale physics drives 0nubb
  - → **A signal would then be within reach of ton-scale conventional experiments.**

- If accessible, this signal is extremely likely to emerge as an indistinct ”hint”.
  - As a statistical excess over a finite background, whose prediction relies on Monte Carlo and detector material assumptions;
  - Nuclear matrix element and physics mechanism uncertainties mean that confirmation with a different isotope will be a “moving target” (although a mandatory step).
  - We must have a plan to resolve to a definitive discovery in an unambiguous, efficient way.
  - Remember that it took 10 years to properly refute Heidelberg Moscow.

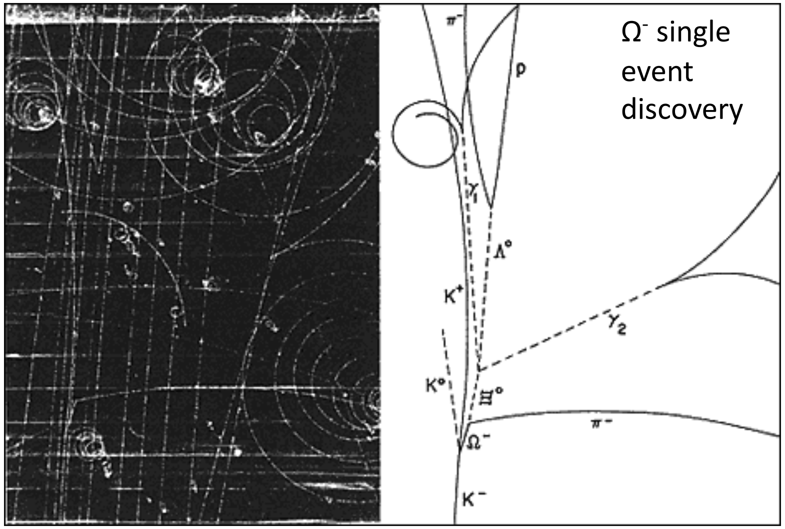
- Confirmation with a new and robust observable within an experiment using the discovery isotope seems the clearest path to confirm or refute a discovery claim.

- Daughter ion tagging is a very promising way to do this, if the technology can be realized.

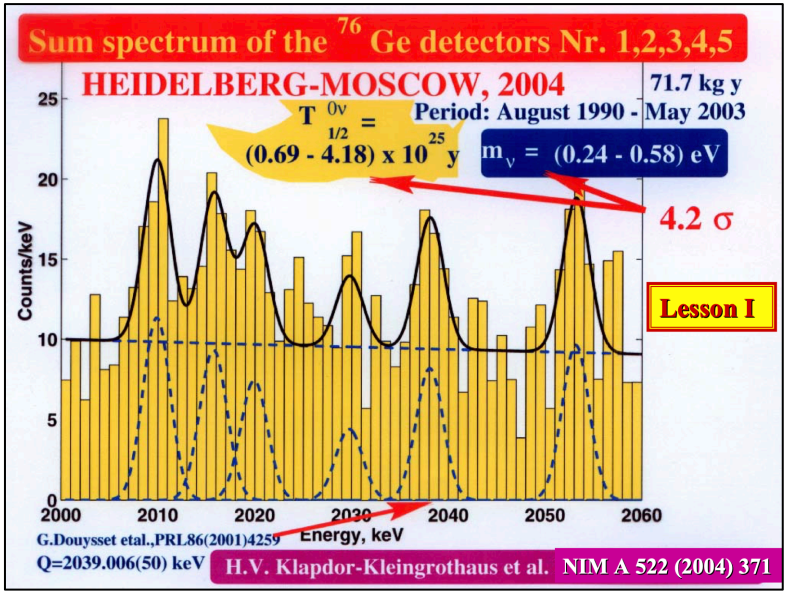
- For the technology to be ready in time, R&D must be continuous from now, and not sidelined while ton-scale experiment construction is ongoing.

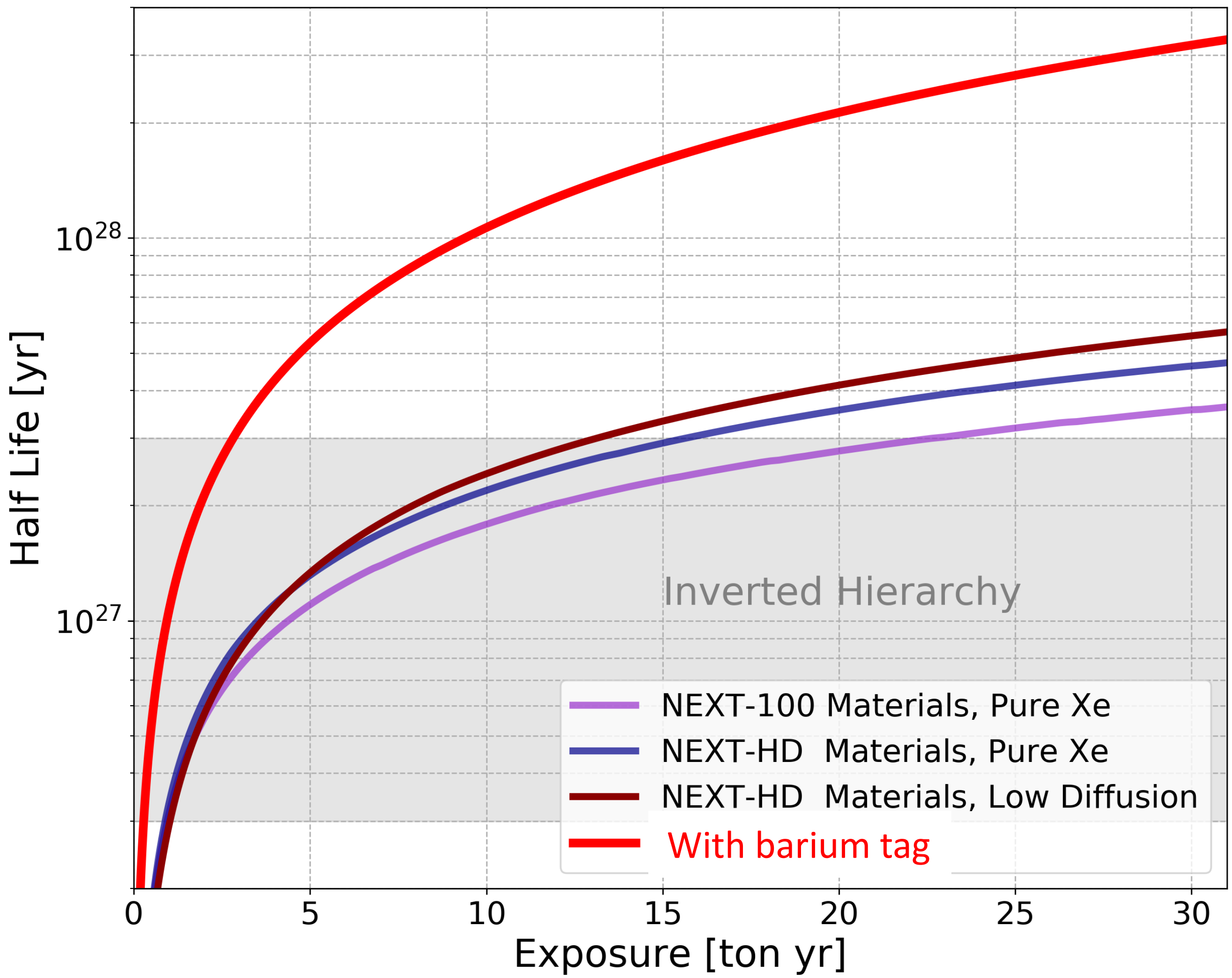
- As a bonus, the reduced background and increased signal efficiency that may be enabled could be the key to reaching into NH sensitivities at multi-ton scales.

Our discovery must be more like this:



And less like this:

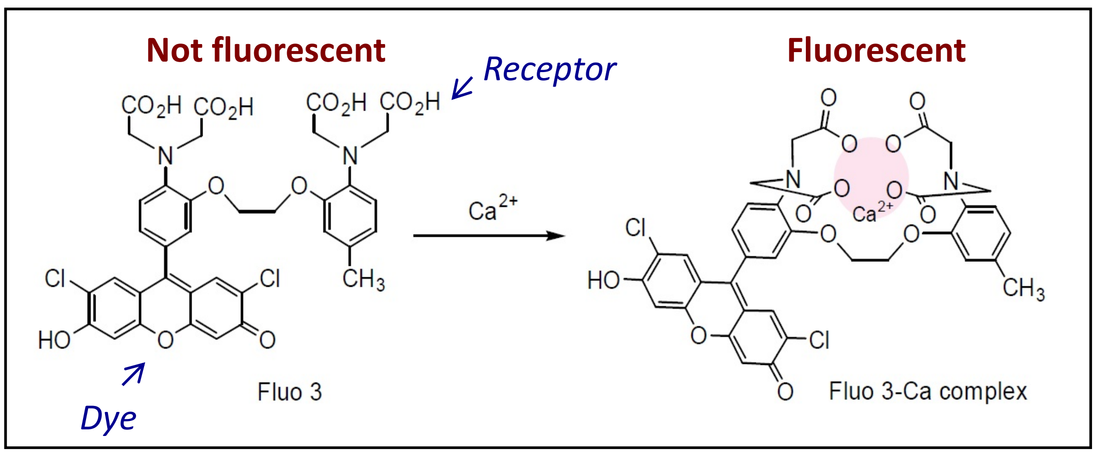


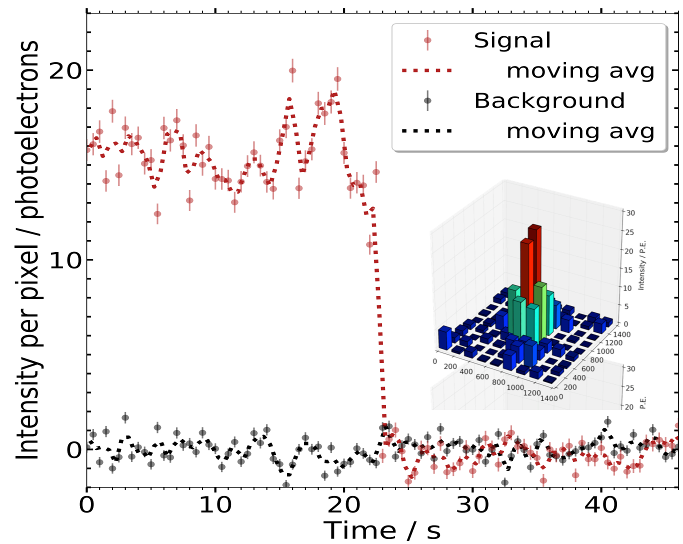


- **Barium tagging gives a dramatic sensitivity improvement through combination of signal efficiency increase and background reductions in high pressure xenon TPCs**

Barium Tagging in Xenon Gas with New Single-Molecule Fluorescence Imaging Techniques

- In xenon gas, barium daughter ions are expected to become ~100% doubly- charged – but there are no low-lying fluorescent transitions.
- Chelation of Ba^{++} by fluorescent chemosensors generates transitions in the visible spectrum under near-UV or two-photon IR excitation.
- New, highly selective chemistry has been realized for Ba^{++} ions.
- Single-step photo-bleaching demonstrates single-molecule sensitivity, with ±2 nm rms super-resolution — well beyond the diffraction limit.





Single-step photo-bleaching in 7 bars of argon gas.

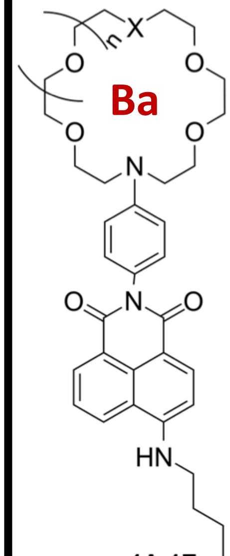
J.Phys.Conf.Ser. 650 (2015) 1, 012002
JINST 11 (2016) 12, P12011
Phys.Rev.Lett. 120 (2018) 13, 132504

New Chemistry

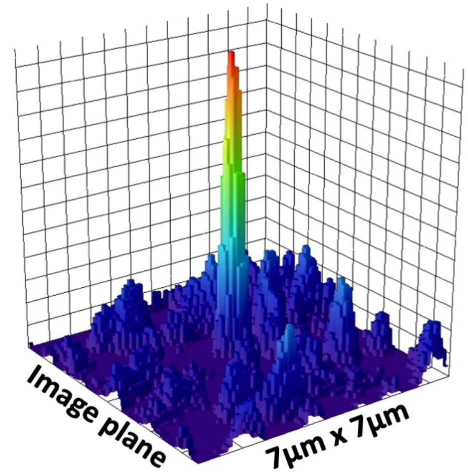
- Conventional ion chemosensors are not suitable for imaging in dry environments such as xenon gas
- NEXT has developed new, dry-phase imaging of barium ions using crown-ether derivatives linked to optimized fluorophores.
- Crown-ether receptor can be tuned to bind efficiently and selectively to barium cations.
- Thus far, two types have been developed within this class of crown-ether chemosensors: **on-off**, and **bi-color.**
- Computational chemistry is predictive for molecular fluorescence and binding.

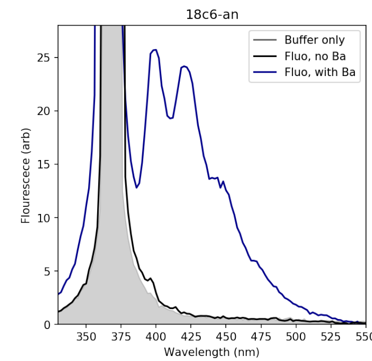
Nature Sci Rep 9, 15097 (2019)
Nature 583, 48–54 (2020)
arXiv: 2006.09494 (submitted to JACS)

Dry single Ba^{++} ion detection with on-off fluorescence

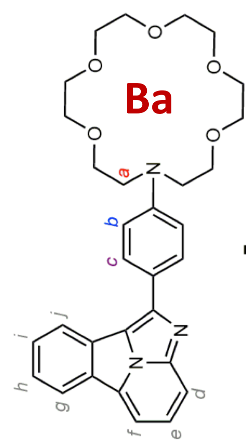


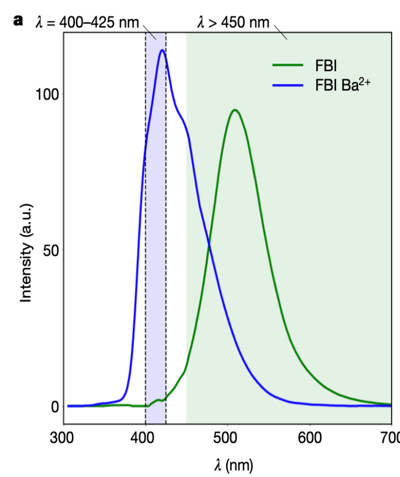
1A-1E





In-vacuo capture from $Ba(ClO_4)_2$ with bi-color response





Fluorescent Bi-color chemosensor switches from green to blue upon chelation; filter removes green light background allowing clean separation

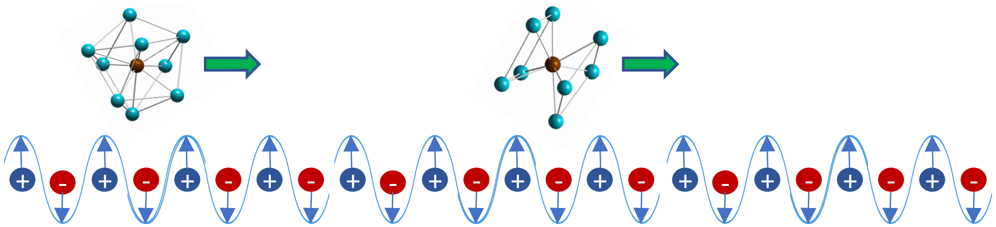
NB: this is outside the scope of this LOI

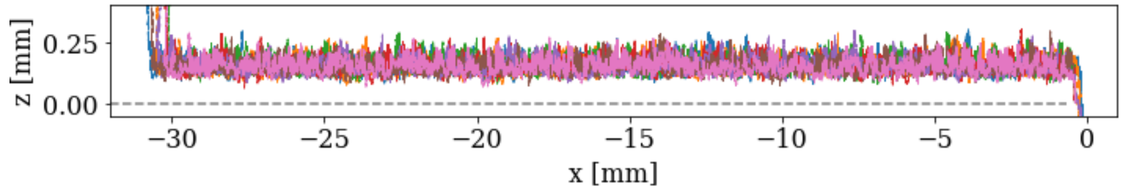
Ion Transport & Concentration: RF Carpets

- One concept for ion collection from a large cathode plane is through concentration with RF carpets at 10 bar onto ~1mm^2 sensor plane with a monolayer of chemosensors.
- Simulations and HV tests suggest that efficient ion transport to sensor plane is achievable at 10 bar xenon, even with solvation shell.
- Program of R&D at the CARIBU facility will test high pressure RF carpet, scheduled for 2020 (COVID permitting).

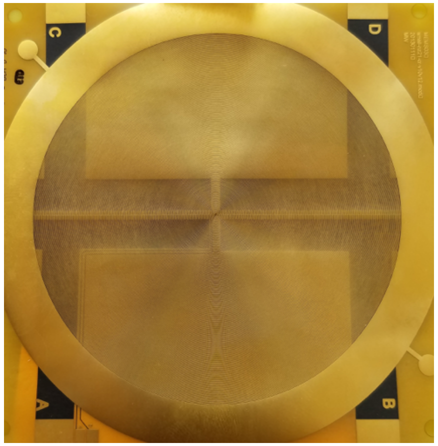
JINST 15 (2020) 04, P04022
Phys.Rev.A 97 (2018) 6, 062509

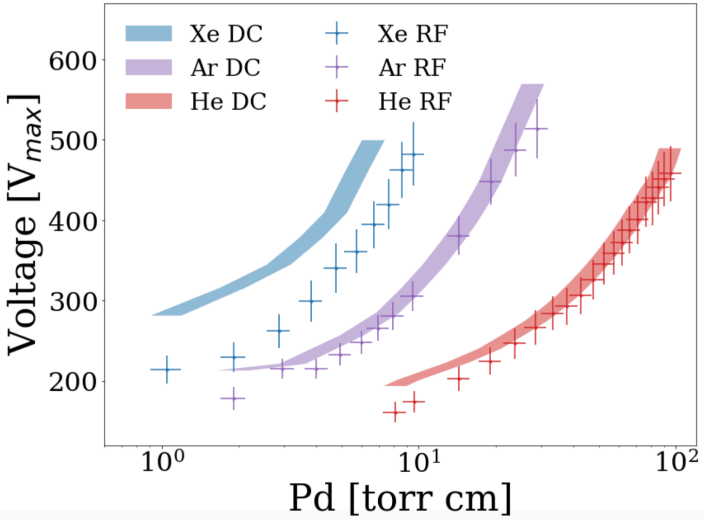
DFT calculations predict ion clustering and RF carpet simulations predict efficient transport.





RF HV strength of Xe is sufficient for RF transport at 10bar.



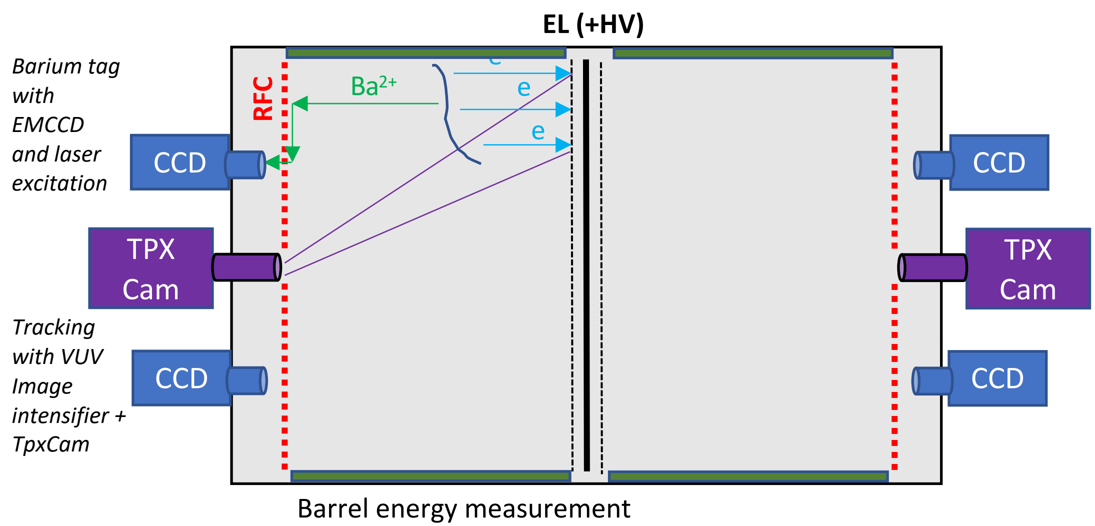


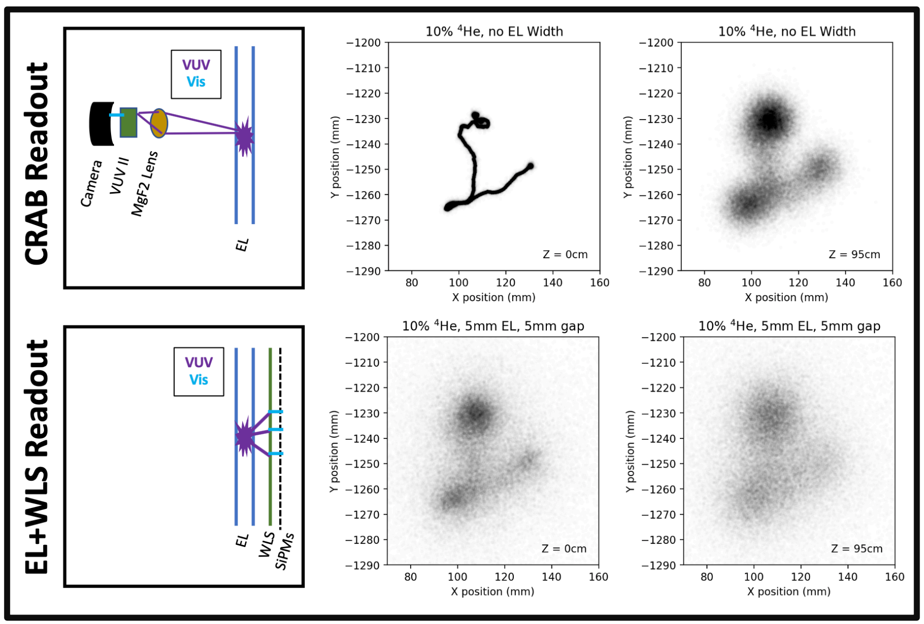
CRAB

Camera **R**eadout and **B**arium Tagging

- **A demonstrator for barium tagging is required to validate the method with 2nubb before extrapolation to large scales.**
- The NEXT collaboration anticipates readiness of this step in 2-3 years.
- To allow for full cathode coverage for ion collection, something in NEXT design has to give (no longer ok to have full energy plane / tracking plane!).
- We are investigating use of direct VUV imaging via high speed TimePix3 camera for tracking.

"CRAB" concept with RF carpet concentrators and camera-based topology measurement





This approach has many advantages, in addition to barium tagging:

- Removes event smearing from WLS plane;
- Massively reduced complexity of tracking readout at large scales;
- Electronics + sensors become external – mitigates issues of radiopurity, heat load.
- Readout is all commercial, via fast optical cameras for tracking and EMCCD cameras for barium tagging.

Pathfinder phase now in construction at ANL.

RF4 questions:

- **What is the physics / motivation for your LOI?**
- **What will you work on between now and Snowmass, and what is your schedule for developing a contributed paper?**
- **What common data sets, joint efforts, etc. do you need?**
- **What would you like to come out of the Snowmass process?**

Thoughts: *(speaking as me, not as NEXT)*

- Work on barium tagging is ongoing in both NEXT and nEXO, following various approaches, in all cases imagined to follow a ton-scale phase of **something** *(which may or may not be xenon)* without barium tagging.

- This is work could be most productively pursued as a community; that community would benefit from input from others outside xenon, outside 0nubb, outside particle physics, and even outside physics entirely.

- We think it would be healthy to lower collaboration walls, to engage in maximally open discussions about barium tagging, and to collaborate on community-wide white papers, looking toward the future.

- We have started some of these conversations with our counterparts in nEXO and will continue these discussions. The ***joint workshops between NF and RF in December and Spring*** on beyond-ton-scale 0nubb techniques will be an ideal place continue to share ideas. Nucleated white papers are presumed to follow.

- ***Out of the Snowmass process we might imagine convergence on a statement such as:***
  - Truly sealing the deal on Majorana neutrinos is one of the highest priorities for our field.
  - A discovery would be so foundational that the burden of proof is extremely high. To this end, it is prudent to look beyond the immediately panned, background-limited ton-scale phases.
  - Beyond-ton-scale 0nubb techniques (of which barium tagging is an example) should be a priority for sustained R&D, for either confirmation of a signal hint or extension of future sensitivities into the NH;
  - The fortified walls separating technologies and collaborations can and should be lowered for the purpose of developing these very challenging new technologies.